An Interactive Garment for Orchestra Conducting: IoT-enabled Textile & Machine Learning to Direct Musical Performance

Berit Greinke*
b.greinke@udk-berlin.de
Berlin University of the Arts
Einstein Center Digital Future Berlin

Giorgia Petri*
g.petri@udk-berlin.de
Berlin University of the Arts
Einstein Center Digital Future, Berlin

Pauline Vierne*
pauline.vierne@gmail.com

Paul Biessmann*
paul@biessmann.de

Alexandra Börner*
a.boerner@udk-berlin.de
Berlin University of the Arts

Kaspar Schleiser*
kaspar.schleiser@fu-berlin.de
Freie Universität Berlin
Einstein Center Digital Future, Berlin

Emmanuel Baccelli*
emmanuel.baccelli@inria.fr
Freie Universität Berlin
Einstein Center Digital Future, Berlin

Claas Krause*
Christopher Verworner*
claas.krause@t-online.de
cverworner@web.de
VKKO Orchestra, Berlin

Felix Biessmann*
felix.biessmann@beuth-hochschule.de
Beuth University Berlin
Einstein Center Digital Future, Berlin

ABSTRACT

We present an overview and initial results from a project bringing together orchestra conducting, e-textile material studies, costume tailoring, low power computing and machine learning (ML). We describe a wearable interactive system comprising of textile sensors embedded into a suit, low-power transmission and gesture recognition using creative computing tools. We introduce first observations made during the semi-participatory approach, which placed the conductor's movements and personal performative expressiveness at the centre for technical and conceptual development. The project is a two-month collaboration between the Verworner-Krause Kammerorchester (VKKO), technical and design researchers, currently still running. Preliminary analyses of the data recorded while the conductor is wearing the prototype demonstrate that the developed system can be used to robustly decode a large number of conducting and performative movements. In particular the user interface of the ML system is designed such that the training of the algorithms can be intuitively controlled by the conductor, in sync with the MIDI clock.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

*All authors contributed equally to this research.

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KEYWORDS

electronic textiles, music, low-power computing, machine learning, interaction design

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1 INTRODUCTION

An orchestra conductor's motion constitutes a distinctive form of communication, combining standardised instructions with personal performative variations. While conductors mostly use hand gestures and eye contact to guide the musicians, conducting is a vigorous full-body act requiring coordination and observant interaction. In this paper we describe an ongoing project which studies the use of e-textile sensors and gesture recognition technologies to track an orchestra conductor's movements. The outcome is a tailored interactive garment which is to be used as a performative musical tool in a live performance of the VKKO. Wearable technology for music is often used to create engaging live performances in which the performer is not hidden behind a laptop screen. These performances rely on the wearable acting as a controller, replacing or enhancing an existing audio interface or digital sound controller. Borrowing musicologist Bielawski's description of musical instruments as *TRANSFORMERS* that transform the gestures of a musician into musical gestures [9], we explore this concept using the garment to transform the conductor's motion into musical gestures. We are interested in shifting the emphasis of a wearable as a control organ and user interface, to a collaborative relationship between the wearer, their motion and actuation.

2 RELATED WORK

2.1 E-textiles for Music Making

Textile interactive materials have been increasingly used to inspire new formats for musical live performances. While sound is not a major consideration in textile design (unless to eliminate unwanted sound), artists and designers have embroidered, woven, knitted, printed and knotted musical interfaces and instruments (e.g. [5, 15, 16, 18]). [14] report on how designers go through the process of exploring textile sensing material and sound output when sensor functionality is not fully determined. [17] use technology probes to explore "creative and disruptive" uses for e-textile sensors in performances that include sound. Bridging textiles with music is also investigated in algorithmic practices, such as live coding [11] and "heritage algorithms" [8] bridging textile crafting and live music making. While e-textiles feature in numerous electronic musical performances, they are little explored in setups involving classical musicians or orchestra ensembles. Examples are mostly restricted to augmenting individual instrument players, e.g. [15]. As a result, these wearables mostly reach audiences which are already familiar with augmented musical performance, limiting the potential of technology to widen the experience of other types of music.

2.2 Wearable IoT Hardware & Software Platforms

In the context of the Internet of Things (IoT), progress in energy-efficient embedded hardware over the last decade has democratised the use of System-on-Chip (SoC) solutions which combine micro-controllers (e.g. Arm Cortex-M, RISC-V, ESP-32...), energy-efficient radios (e.g. Bluetooth Low-Energy, IEEE 802.15.4...) and a variety of sensors, GPIOs etc. As such, a SoC amounts to a tiny single-board computer which can connect to the network. Basically, compared to microprocessor-based hardware, a SoC trades off smaller computing and memory capacities for a smaller energy consumption. The power consumption of a SoC in this category is typically in the milliwatt (mW) range, thus a very small battery can suffice. In some cases, battery-less operation is even a perspective [1]. All in all, the relative low price (10€) and small form factor (thumb-sized) make it possible to embed such systems in a variety of wearables e.g. smart watches [2] or electronic tokens sewn into clothing items.

A variety of open source embedded software platforms and open specification protocols have been developed to interact with and programme such pieces of hardware. For simple use cases, Arduino or Micropython scripts can be used, for instance. For more advanced programming and performance fine-tuning, a variety of real-time embedded operating systems are available [6]. To interoperate with remote elements in a distributed system, a SoC network connectivity and security can be provided by adapted standard Internet protocols [13, 19].

2.3 Machine Learning for Musical Expression

Machine Learning (ML) has been used for over 25 years for New Interfaces for Musical Expression (NIME, see [3] for review). Various many open source libraries are currently used to enrich musical live performances, such as tensorflow [12]. New open source software makes it simple to build ML models in the browser [10] and to use ML models with digital audio workstations (DAWs) [4]. There is exciting research aiming at novel ML models, for instance for sound generation [12]. Using the tool Wekinator [2] in this work, we chose to employ ML methods primarily to improve usability of textile sensors with unknown functional properties.

[1] ONiO.zero energy harvesting MCU https://www.onio.com/article/onio-zero-batteries-mcu.html
[2] PineTime low-power smart watch https://www.youtube.com/watch?v=WdOHOHGS0d8

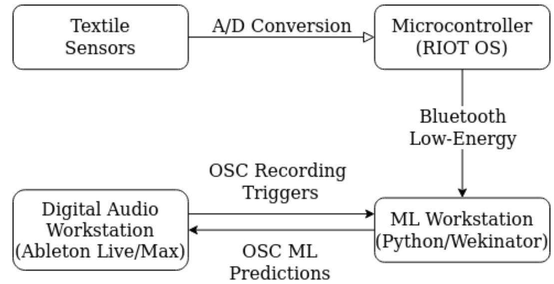

Figure 1: e-Textile prototype: IoT system architecture.

3 METHODS

Qualitative and quantitative methods were combined, linking technical evaluation with material experiments, conceptual tailoring and interaction design considerations. While the project is still in progress, we can provide a first overview of methods.

- Observations of the conductor's motion, recorded as notes and drawings by the research team members during weekly rehearsal sessions. Each team member was tasked with observations that would fall into their disciplinary domain (e.g. textile researcher inspecting e-textile responsiveness; ML developer inspecting ML performance; etc.) to gain a comprehensive understanding of the entire system.
- Recorded sensor data was analysed and linked to video recordings of the conductor. The videos were transcribed when oral feedback from the conductor provided additional insights.
- Iterative prototyping was used to assess material functionality, aesthetics and interaction. We started from a simple textile sensor layout that allowed use of an interactive jacket already early in the project. Design options were discussed with the conductor and team, and next steps decided.

4 EXPLORATORY STUDIES

In this section we describe the underlying performance context and the design process. Technical iterations were done in parallel with conceptual work.

As a preliminary technical step, we developed a generic wireless wearable IoT system architecture depicted in Fig. 1. A low-power SoC uses RIOT [1] and Bluetooth Low-energy to interconnect in real-time the analogue output of textile sensors, with a Machine Learning workstation (based on Wekinator [3]) and a digital audio workstation (running Max and Ableton Live). The textile wearable

[3] http://www.wekinator.org

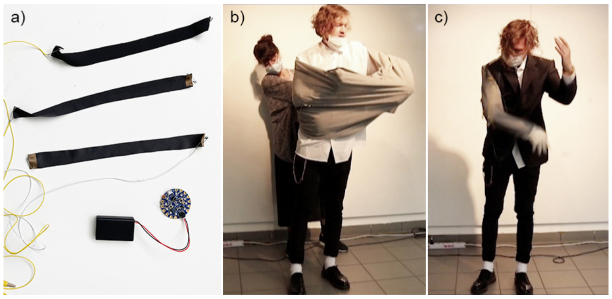

Figure 2: Initial prototypes: (a) Stretch sensors (b) Knitted tube (c) jacket with modular attached stretch sensors

was developed in three stages. We started with a modular sensor setup, exploring potential types and placements for textile sensors based on a conductor's jacket. In the second stage the sensors were adapted towards interaction. In the third stage a prototype was developed for performance on stage.

4.1 Concept

VKKO blends traditional acoustic instrument playing with electronic soundscapes and improvisational jazz. Describing themselves as a "music machine" that brings together "contemporary classical music and Dub Techno, Neo-Impressionistic string-clouds and dense Electronic Rhythms"[4], VKKO's live performances bridge classical music with dance floor experience. The number of performing musicians varies between 12 and 18. The orchestra was founded by two conductors and composers, who also act as artistic directors. Both conductors themselves also combine operative conducting with performative elements, seamlessly linking standardised conducting movements (e.g. beat patterns) with expressive movements usually more associated with club or alternative music culture (e.g. headbanging). For the work described here, we focused on one of the two conductors. At the time of writing this paper, the performance structure was not finalised. However the concept and the succession of musical parts was discussed throughout the collaboration. The development of the textile technology and an ML setup appropriate for the conductor's movements also has an influence of the development of the composition.

4.2 Preliminary prototypes

The aim of the first textile exploration was to get an understanding for the conductor's response to an interactive garment with a sound feedback. Two prototypes were made:

(1) Knitted tube for performative aspects: Exploring how the conductor deals with restricted movement;
(2) Suit jacket for standardised movements aspects: Exploring how the conductor deals with a familiar garment.

Sensor layout and materials: Three stretch sensors were made, using Eeonyx LTT-SLPA-20 as a variable resistors strips, and Shieldex Technik-tex P130+B to stabilise the ends (Fig. 2). The sensors were attached to the base fabrics with safety pins, and maintained in place with additional fabric pins.

[4]http://www.kammerorchester.eu/info

Technical results: Investigating general functionality of sensors in this session, we made following observations:

- All sensors were responsive. Sensor ranges for tube were larger than for jacket due to stretch capability of tube fabric, and use of hands and arms inside the tube for additional stretch.
- The placement of sensors was adjusted during testing to identify areas for most stretch. Other areas on the jacket that appeared to have larger movements were marked with tape for potential sensor placement in the next step.

Interaction observations: Upon being dressed with both prototypes, the conductor began exploring the sound response in relation to his movements. Despite no previous experience with body-worn sensors, he felt comfortable immediately in both prototypes. Observing his movements, we identified four 'movement modes':

- Classic conducting moves: Standardised patterns or expressions, e.g. beat patterns;
- Signature performative movements: Personal movements or expressions which the conductor uses regularly or has used in previous performances;
- Try and learn: Adapting existing movements while familiarising with sensor positions, reactions and sound response;
- Performative control: Bolder movements that result from being informed about sensor placement and function, paired with performative curiosity.

These were often combined or performed in short sequences flexibly put together. An important aspect during this phase of exploration was that the movements should be distinguishable by both the ML algorithm as well as the audience. This helped guide the exploration towards simpler and more expressive or performative movement types.

4.3 Improved Prototype for Interaction Exploration

Over the next five rehearsal sessions, the 'jacket' prototype was used as a basis for further development. The goals were to:

- Explore textile sensor technologies for better integration and refined aesthetics, adapted to observed movement patterns.
- Gesture following and interaction with system

Sensor layout and materials: It was important to provide sensors with robust behaviour, delivering repeatable electrical and mechanical performance. Further material experimentation was conducted in parallel, studying in-situ polymerisation [7][5] for customising sensor placement and aesthetics. The microcontroller was securely fastened on the jacket and fitted with snap buttons. Cables were replaced by conductive copper threads encased in thin knitted tubes.

Technical results: We recorded data from six sensors with the prototype during a series of movements (see Figure 3) and analysed the data with respect to the dynamical properties of the sensors and their dependency on various movement types. In Figure 4 we show that different sensors and sensor placements can have very different dynamic properties. In this case, sensor 1 (channel 0) on the right elbow was very responsive and captured distinct high

[5]see https://hackaday.io/project/168380-polysense for an updated recipe

No.	Location	Type
1 (ch0)	Right elbow (out)	Stretch sensor strap
2 (ch1)	Back (horizontal)	
3 (ch2)	Right shoulder	Resistive knitted tube
4 (ch3)	Left armpit	Pressure sensor foam
5 (ch4)	Left shoulder	
6 (ch5)	Right elbow (in)	Resistive knitted tube

Figure 3: a) Movement 1: Resting position b) Movement 2: Fermata c) Movement 3: Expressive entrance d) Movement 4: Hush e) Movement 5: Attention 'rhythm section'. Right: Sensor distribution.

	Sensor 1 (ch 0)	Sensor 2 (ch 1)	Sensor 3 (ch 2)	Sensor 4 (ch 3)	Sensor 5 (ch 4)	Sensor 6 (ch 5)
Location	Right elbow (out)	Back (horizontal)	Right shoulder	Left armpit	Left shoulder	Right elbow (in)
Type	Stretch sensor strap	Stretch sensor strap	Resistive knitted tube	Pressure sensor foam	Pressure sensor foam	Resistive knitted tube

Table 1: Overview sensors improved prototype

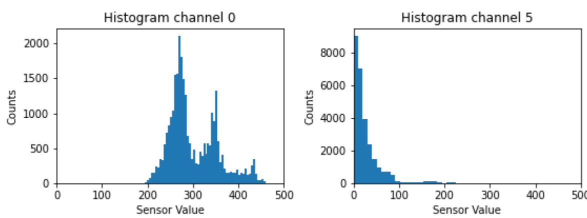

Figure 4: Histograms of two different textile sensors illustrating different conductive properties and how they relate to sensor responses to different movements. *Left:* Histogram of sensor 1 shows pronounced peaks for different movement types; the sensor captures a wide dynamic range of values. Sensor 6 shows very different properties, with most values being close to zero and some few large values.

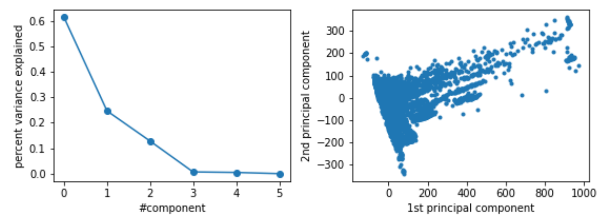

Figure 5: Principal Component Analysis (PCA) of 6 sensors recorded during different movements. *Left:* Variance of all sensors explained by individual principal components (PCs). The first and second PC explain more than 80% of the variance. *Right:* First and second PC capture the same sensor dynamics as in Figure 4, representing the two sensor types.

density regions of sensor values with different movements, while other sensors were less responsive to movements and only showed peak activation for very few values. We conclude that, as expected, the types of sensors and their location have a direct and strong effect on the statistical properties of the recorded signals.

Next we analysed the principal directions of variance in the data using principal component analysis (PCA). In Figure 5 we show the variance explained by individual principal components (PCs). Most variance is explained by the first two components and the statistical properties of the two first PCCs reflect the two types of sensors whose histograms are shown in Figure 4.

After analysing the data of all movements in aggregation, we also investigated how well a ML model can predict the different movements from the sensor activation in offline experiments. The results of this offline analysis is shown in Table 1. We performed an 80%/20% train/test split of the recorded data and used a k-Nearest Neighbor (KNN) classifier with $k = 3$ (optimised with grid search) to predict each one of the five movement types performed. The results in Table 2 show that all movements in the test set could be predicted with perfect accuracy, precision and recall. This shows that despite the different sensor properties, illustrated in Figure 4, a simple ML model was able to predict the correct movement type reliably. We conclude that the prototype yields data that can be easily modelled with a ML model for transforming the sensor readings into control signals defined by the conductor, or more generally the user of the prototype.

Interaction observations: These sessions focused on improving the sensors' electrical resistance range and investigating suitable ML models. Over the course of five weeks, the conductor learned how movements were related to success of gesture recognition, and developed a repertoire of suitable static positions and gesture sequences. For the performance set up, two ML methods were selected:

- Classification to learn and recognise fixed body positions: Used to trigger big audio events
- Regression to learn and recognise movement sequences: Control continuous sound values (e.g. volume, filter)

	Movement 1	Movement 2	Movement 3	Movement 4	Movement 5	accuracy	macro avg	weighted avg
precision	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
recall	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
f1-score	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
support	39.0	45.0	37.0	39.0	46.0	1.0	206.0	206.0

Table 2: Results of offline analyses of movement classification with a simple ML model demonstrate robust and high quality predictions are possible with the prototype.

Sensor (channel) No.	Location	Type
1 (ch0)	Right shoulder	PolySense non-woven substrate, *pressure sensor*
2 (ch1)	Left shoulder	
3 (ch2)	Back	PolySense mesh fabric, *stretch sensor*
4 (ch3)	Left elbow	Eeonyx LTT-SLPA-20 and PU foam, *pressure sensor*
5 (ch4)	Right elbow	
6 (ch5)	Left knee	

Figure 6: Jacket part of tailored interactive suit, and sensor distribution.

4.4 Final prototype: Tailored Costume

In the final design step, the jacket prototype was used as a blueprint for tailoring a suit-based garment for the conductor (see Figure 6), adapted to sensor use and performance settings. The goal was to create a garment with a fit similar to the prototype so far, allowing us to reuse textile sensors and electronic set up. The final prototype is currently used for rehearsals for an upcoming performance. Therefore technical results and interaction observations can not yet be described.

Sensor layout and materials: A different type of textile material was used (polyester gaze) which resulted in a considerably stiffer jacket. This required an altercation of all sensors, because it limited the stretch of sensors previously tested. In addition, the outer material exerted additional force onto the sensors. All final sensors were mounted onto a lining (polyester mesh and cotton calico), with customised material, shape and fit. Two sensors used in-situ polymerisation on non-woven fabric (both shoulders), sandwiched between two layers of conductive stretch fabric, forming pressure sensors. A stretch sensor mounted across the back was prototyped from polymerised spacer mesh fabric. Two sensors mounted on the insights of the elbows, and one sensor on the right knee, were made from Polyurethane foam and Eeonyx LTT-SLPA-20 stretch fabric.

5 DISCUSSION

We would like to reflect on a few first insights:

5.1 E-textiles

To support performative collaboration between conductor and suit, textile sensors have been developed specifically for conducting movements. We used an in-situ polymerisation technique that allowed us to define shape, dimensions, and base materials. More time is needed to make the process controllable, however we have shown that sensors prototyped this way, even in a DIY setup, are a reliable alternative to store-bought sensor materials for our purpose.

5.2 Gesture recognition and following

Applying creative computing tools allowed the team to progress consistently. The mapping between gesture and sound can be intuitively defined by the conductor, simply by recording some training data. It also enabled a rapid development progress for the entire team: Once a new prototype was made with different materials, shapes and sensors, we were able to train the ML algorithm without any modification on the software side. Importantly the recording of training data was synced with the MIDI clock of the digital audio workstation (DAW) and the recordings were triggered by the conductor himself. Of the three tested methods, classifying static poses has been the most reliable method, achieving 100% accuracy during most rehearsals. It should be noted that new training is needed as soon as the prototype is used in a different way or at different times of the day. Given the sensitivity of e-textiles to environmental conditions and wear, sensor reading can vary vastly. There is more work to be done to investigate if this could, for example, be solved by adding training data over longer time.

5.3 Interaction

The VKKO conductor garment is an interesting use case for several reasons. First, the combined operative and performative movements allowed us to explore reliability and repeatability on the one side, and less predictable but more collaborative interaction between wearer and garment on the other side. Second, the conductor was comfortable in his role and used to a scenario in which (albeit in different ways) his movements lead to a musical response. This enabled us to enter the iterative prototyping stages promptly and helped to focus on technical and interaction development. While a final assessment of interaction cannot be given at this time, the rehearsals have shown that the systems recognised both standardised and personal performative movements, and were used creatively by the conductor to manipulate sound output.

6 CONCLUSION AND OUTLOOK

While the project is still ongoing, we have developed a proof of concept and prototype for an interactive conductor's suit. We have demonstrated that gestures of the conductor can be recognised and used for performative action, employing e-textiles, low-power computing and machine learning. In summary, we believe that our system can complement existing work on ML software libraries by helping to further democratise the usage of ML tools in creative disciplines, including textile wearable technology. First results of e-textiles development, sensor performance and interaction observations, have been described. In the next step we will analyse video and sensor data in detail, to gain more insights about the technical developments. Following the performance of the orchestra in

November 2020, our focus will be to learn about the conductor's approach to interact with the system in orchestra rehearsals and live performances.

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